

High-average-power second-harmonic generation from periodically poled silica fibers

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The generation of 236 mW of second-harmonic power in a 32-cm-long periodically poled silica fiber, corresponding to an average conversion efficiency of $15.2 \pm 0.5\%$, is reported. This represents the highest normalized second-harmonic conversion and the highest average second-harmonic power ever reported for a periodically poled silica fiber, to our knowledge. The enhancement is attributed to an improved design of the specialty twin-hole fiber and the extension of the nonlinear interaction length. © 2009 Optical Society of America

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Fiber lasers in the visible spectrum are typically ytterbium- or erbium-based sources that are frequency doubled with nonlinear crystals. The complexities associated with launching light from fiber lasers into bulk crystals, the high coupling losses, and the low damage thresholds associated with such are some of the disadvantages that are typically considered inescapable for the generation of visible wavelengths. Nonetheless, it is known that the process commonly referred to as thermal poling can induce a permanent $\chi^{(2)}$ in a variety of glass compositions, optical fibers, and waveguides [1,2]. Phase-matched frequency doubling is possible through periodic poling, as with noncentrosymmetric crystals. Periodically poled silica fibers (PPSFs) are therefore an attractive all-fiber solution to frequency conversion of high-power fiber lasers. The excellent optical properties of silica-based fibers together with the ruggedness intrinsic of all-fiber solutions allow one to overcome the drawbacks of coupling to bulk crystals. Moreover, despite having a lower effective nonlinear coefficient, they can offer longer interaction lengths for comparable acceptance bandwidths to periodically poled ferroelectric crystals, owing to the lower chromatic dispersion of glass. Operation at virtually any wavelength is possible by varying the quasi-phase-matching (QPM) period [3,4]. Furthermore, broadband tunability at room temperature can be obtained by simply compressing or stretching the fiber devices [5]. A 20% average conversion efficiency was demonstrated in an earlier work by frequency doubling 1.5 μm laser radiation with the generation of 6.8 mW second-harmonic (SH) power [6]. Spontaneous parametric downconversion led to a photon-pair generation, opening the way to a source of entangled photons [7,8]. This and other applications will greatly benefit from high-power, good-beam-quality SH generation (SHG).

In this Letter, the generation of as much as 236 mW SH light from a PPSF pumped by a high-

power fiber laser is demonstrated. The result shows the ability of the PPSF to handle high-average pump powers (~ 1.6 W) without any signs of decay of the second-order nonlinearity from day to day operation. The SH average power shows a 35-times improvement over the best results on PPSFs to date [6], and the corresponding average efficiency exceeding 15% was achieved with 20-times lower peak power.

A $\text{GeO}_2/\text{SiO}_2$ fiber with fused-silica cladding of NA=0.11 and second-mode cutoff of 770 nm was fabricated with two holes of ~ 45 μm diameter positioned on either side of the core, as shown in the inset of Fig. 1. The NA, closely matching that of the commercial SMF-28 single-mode fiber, was chosen in order to minimize the splice losses between the two and with the output of the erbium/ytterbium fiber laser

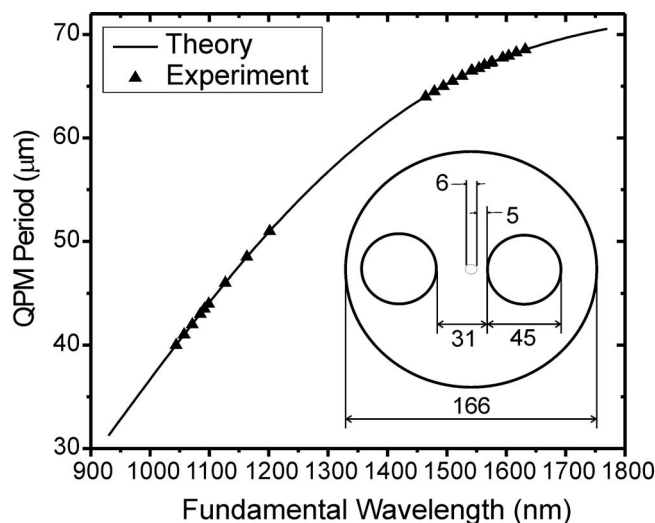


Fig. 1. Relationship between the QPM period and the fundamental wavelength for PPSFs fabricated (triangles) and theoretical curve (solid curve) determined from the index profile of the fiber. Inset, schematic of the twin-hole fiber used for this work (dimensions are in micrometers).

source to be frequency doubled. The splice losses to SMF-28 fiber were measured to be 0.5 dB at 1550 nm and 1.0 dB at 780 nm. Compared with splice losses, transmission losses are negligible over the typically short lengths used for the fabrication of periodically poled devices.

The high dc poling voltage (11 kV) was applied through tungsten wires of 30 μm diameter inserted into the holes. The optimal poling conditions (210°C, 1 h) were determined by poling several fiber samples at a range of temperatures and monitoring the evolution of the electro-optic coefficient using a Mach-Zehnder interferometer. The relatively low poling temperature was chosen in order to slow down the dynamics of the formation of the second-order nonlinearity (SON). The positive voltage was applied to the electrode closest to the core as the nonlinear region is formed in the region of the anode.

A frequency-doubled argon-ion laser operating at 244 nm cw is employed for the point-by-point periodic erasure of the poled region, creating a QPM structure to compensate for the mismatch in the phase velocities of the copropagating fundamental and generated SH waves. The UV erasure parameters, fluence, and duty cycle were optimized for this fiber. Several periodically poled fibers were fabricated for frequency doubling of a range of different wavelengths (Fig. 1). The period of the $\chi^{(2)}$ -grating, Λ , for phase matching at the desired pump wavelength, λ , was determined from $\Lambda = \lambda / 2(n_{\text{eff}}^{2\omega} - n_{\text{eff}}^{\omega})$, where n_{eff}^{ω} and $n_{\text{eff}}^{2\omega}$ are the effective indices of the LP_{01} mode at the first-harmonic (FH) and SH wavelength, respectively. The mode indices have been calculated from the fiber refractive index profile, measured at 632.8 nm, using a commercial profilometer and corrected to the FH and SH wavelengths via Sellmeier's equations for Ge-doped silica fibers. The agreement between the experimental data relating the $\chi^{(2)}$ -grating period with the QPM-wavelength for all the PPSF devices fabricated over a 500-nm-wide spectral range and the theoretical curve is outstanding and shows the good uniformity of the fiber and the exceptional reproducibility of the point-by-point UV erasure technique (Fig. 1).

For this demonstration a 32-cm-long PPSF device of QPM period of 66.5 μm was fabricated at optimized poling and UV erasure conditions for frequency doubling of a fundamental wavelength within the high-gain region of an erbium/ytterbium fiber-laser source. The length of 32 cm is the longest PPSF fabricated to date (to our knowledge), with longer lengths limited only by the translation stage used for the periodic UV erasure.

The PPSF device was initially tested using a 9 mW cw tunable external-cavity diode laser. The SH tuning curve was obtained by scanning the wavelength of the low-power cw laser and recording the corresponding SH power (inset of Fig. 2). The acceptance bandwidth of the device was measured to be 0.46 nm, in agreement with theoretical predictions. The almost perfect sinc^2 profile of the tuning curve is a testament to the extremely good quality of the QPM grating over the entire 32 cm length. From this mea-

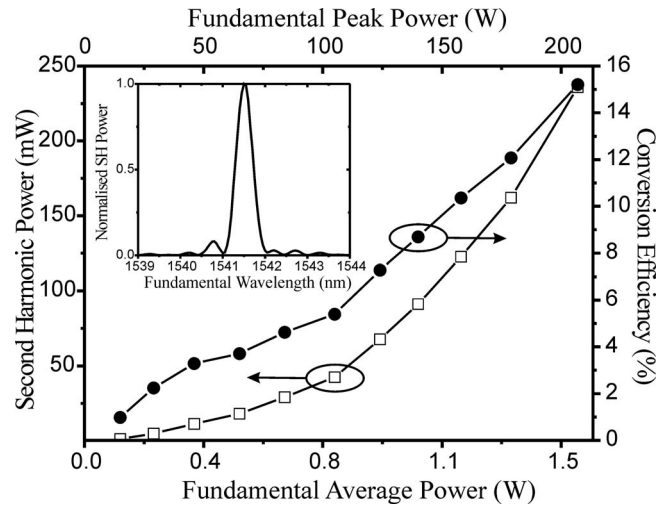


Fig. 2. Average SH power (squares) and average conversion efficiency (circles) measured as a function of the fundamental power for the 32-cm-long PPSF device. Inset, SH tuning profile obtained with the low-power external-cavity tunable cw diode laser.

surement, the normalized conversion efficiency was estimated to be $7.34 \times 10^{-2} \text{ \%}/\text{W}$, translating to a 3.3-fold improvement over the previously best reported value [9] and 14-fold over [6].

The periodically poled fiber was then utilized for the frequency doubling of a high-power, narrow-linewidth, pulsed fiber-laser source delivering 2.5 ns pulses at a repetition rate of 3 MHz. For pulses of duration $\tau = 2.5 \text{ ns}$, there is no significant walk-off between FH and SH pulses in the fiber used for this work ($L_W \equiv \tau / \text{GVM} \sim 64 \text{ m}$). The laser is based on a single-frequency tunable source externally modulated and amplified through a single mode and double-clad amplification stages [10]. The average output power was 1.8 W with a single-mode SMF28 fiber output.

The quadratic dependence of the average SH power at the wavelength of 771.75 nm against the fundamental source power operating at 1541.5 nm is shown in Fig. 2. The average conversion efficiency is also shown in Fig. 2 for increasing fundamental power. The maximum average conversion efficiency was calculated to be $15.2 \pm 0.5\%$ with just 207 W of fundamental peak power. The minor deviation from the expected linear response seen in the conversion efficiency is attributed to the variation in the ratio of the power contained within the narrow linewidth to the amplified spontaneous emission power in the fundamental source. The generated SH did not appear to decay, even with repeated and prolonged testing with the high-power fiber-laser source, and the same value of SON was measured months after the experiments. The obtained average SH power of 236 mW, contained within the LP_{01} mode, is the highest obtained in a PPSF device to date.

The measurements of the conversion efficiency obtained in several samples enabled us to estimate the value of the nonlinear coefficient induced by poling in $d_{33} = 0.054 \pm 0.002 \text{ pm/V}$. Despite the different fiber design, this value does not represent a significant en-

hancement compared with earlier works in periodically poled silica fibers. The value is twice as large as in [6], but the improvement is somewhat reduced by the smaller power density of the fundamental mode owing to the reduced confinement determined by the fiber cutoff. The nonlinear coefficient is also approximately 5 times smaller than the typical nonlinear coefficients achieved in bulk glasses $d_{33}=0.3$ pm/V. For comparison, see $d_{32}=0.85$ pm/V in lithium triborate, $d_{22}=2.3$ pm/V in beta-barium borate, and $d_{36}=0.39$ pm/V in potassium dihydrogen phosphate [11]. Several factors can contribute to these reductions, including (a) a nonoptimal overlap between the core and the nonlinearity; (b) the lower impurity concentration of optical fibers fabricated by modified chemical vapor deposition, compared to fused-silica bulk glasses [12]; (c) the core-cladding interface hindering the migration of charges [13,14]; (d) the comparable thickness of the depletion region to the distance over which the electric field is applied in optical fiber in comparison with bulk glasses [12]; and (e) a nonoptimal modulation contrast of the $\chi^{(2)}$ grating. However, it is significant that 15% conversion efficiency with the generation of over 230 mW of SH power was obtained in this work despite the relatively small value of the SON. Since the conversion efficiency, η , scales quadratically with the SON ($\eta \propto d_{33}^2 L^2 P^\omega$, with L being the length of the PPSF and P^ω the power of the fundamental beam), efficiency exceeding 50% will be possible by optimization of the factors mentioned above.

The previous report of high conversion efficiency was achieved with a very high peak power source (4 kW), as the length of the device was limited to 7.5 cm by the employed photolithography technique [6]. The technique of uniform poling and subsequent point-by-point UV erasure described above overcomes this fundamental limitation and makes the fabrication of long PPSF devices feasible [9]. The improvement reported herein is due for the greater part to the ability to fabricate long periodically poled fibers, compensating for the relatively low effective nonlinearity and enhancing the conversion efficiency through the quadratic dependence of SH power with interaction length.

In conclusion, high-average-power SHG was demonstrated in a PPSF fabricated using highly repeatable techniques of thermal poling and UV periodic erasure. The average power and normalized conversion efficiency have been significantly enhanced over previous reports through the improved fiber design

and optimized PPSF device fabrication. A conversion efficiency of 15.2% was demonstrated, limited by the relatively moderate power available from the used fiber laser source. Conversion efficiency of over 50% is theoretically possible by fabricating twice-as-long devices, by doubling the effective nonlinearity or by making use of fiber laser sources having ~ 1 kW peak power.

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